AN INVESTIGATION OF STRESS CONCENTRATION FACTORS AROUND SELECTED OPENINGS USING THE BRITTLE LACQUER TECHNIQUE

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Submitted to the Faculty of
Rensselaer Polytechnic Institute
In Partial Fulfillment of the
Requirements for the Degree of
Master of Civil Engineering.

by

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TROY, NEW YORK
SEPTEMBER, 1948

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ACKNOWLEDGMENT

The investigators wish to acknowledge their indebtedness to Professor R. H. Tratnen, Mechanics Department, for his constant interest in the topic and his invaluable suggestions throughout the entire project. The authors are also indebted to Admiral L. B. Combs, Head of Civil Engineering Department, for his assistance in obtaining the services of the machine and welding shops at the Scotia Naval Depot; to the Public Works Department of Scotia; to Mr. David Howells II, Supervisor of Purchases, R.P.I., for his energetic service in obtaining many critical materials; to Mr. J. F. Throop, Materials Laboratory, for his suggestions in use of the laboratory equipment; and to Mr. George Sprong, machinist of Materials Laboratory, for his good-natured and skillful ability in helping prepare the test plates.

The investigators also wish to express their appreciation to all persons of the Bureau of Yards and Docks who cooperated so completely in furnishing the necessary details to initiate this project.

ABSTRACT

The objectives of this study were twofold. The first was an investigation of the use of the relatively new technique of brittle lacquer for determining quantitatively certain stress concentration factors. The succeeding objective, depending on satisfactory results of the first, was the actual determination of the factors for certain selected openings of particular shapes and sizes.

The authors have attempted to point out the practical problems and considerations involved in the use of brittle lacquer for a study of this kind. It was found that the technique is quite practicable, especially for odd shaped pieces or openings and that for large scale operations the investment in the brittle lacquer equipment and its use would be advisable.

The factors obtained for the particular openings used in this project are found in the data section of this report.

INTRODUCTION

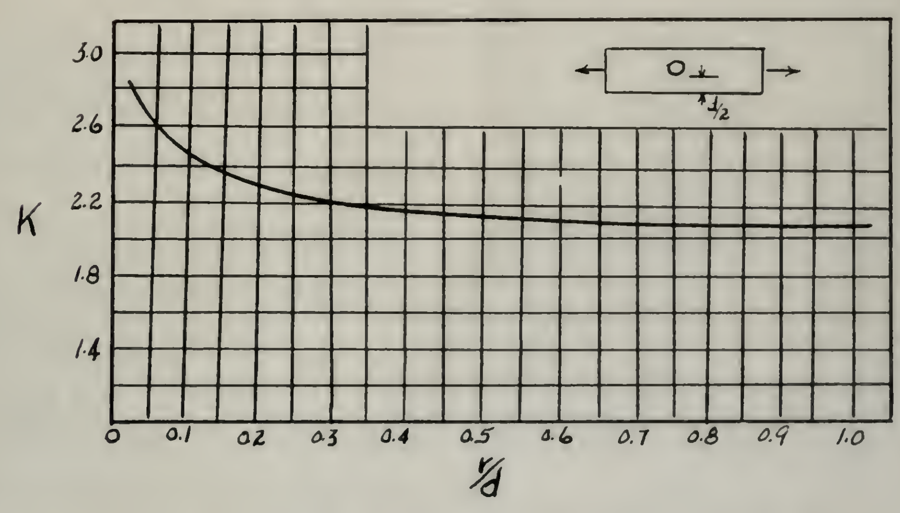
The object of this investigation was to determine if brittle lacquer could be successfully used to investigate stress concentration factors around circular, semi-elliptical, and bi-elliptical openings in flat plates subject to uniaxial loading; and, if so, to determine the stress concentration factors around these selected openings.

The term stress concentration factor as used in this paper is defined as the ratio of the maximum stress to the average stress in the minimum section. The term bi-elliptical opening is used in referring to openings consisting of halves of two ellipses having a common major intercept but different minor intercepts.

The importance of stress concentration factors around commonly used openings is obvious and has been the subject of considerable research and study. The particular openings chosen for this investigation were suggested by the Bureau of Yards and Docks of the U. S. Navy. They consisted of openings which are commonly used in drydock and tunnel construction and about which there is very limited data available. The tunnel pillar problem constituted one set of openings investigated. This consisted of semi-elliptical openings with bases along a common line separated by pillars of varying depth. The importance of this problem is obvious in tunnel

work and other construction where openings of this type are frequently used.

The problem of stress concentrations around simple openings, such as a small circular opening in a plate of infinite width, is one which has been thoroughly analyzed and studied. The theoretical analysis of this problem gives a stress concentration factor of three where the width is great compared to the diameter of the hole. The variation of the factor with the ratio of radius of hole to width of plate is reproduced below from "Strength of Materials"--Part II by S. Timoshenko. It can be seen that the factor



decreases considerably as the ratio r/d increases.

For elliptical holes the following is quoted from the above reference: "In the case of a small elliptical hole in a plate the maximum stress is at the ends of the horizontal axis of the hole, and is given by the equation:

$$f\ max. = f(1 + 2\ a/b)$$

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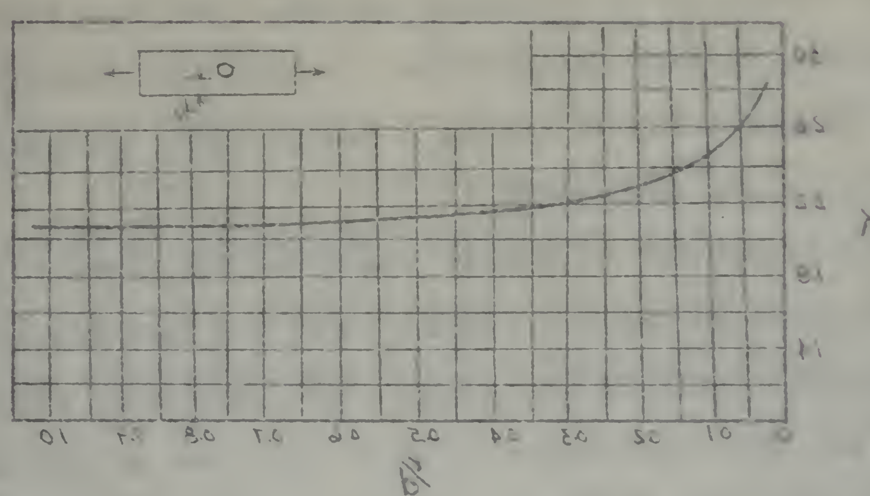

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For elliptical holes the following is quoted from the above reference: "In the case of a small elliptical hole in a plate the maximum stress is at the ends of the horizontal axis of the hole, and is given by the equation

$$\sigma_{max.} = S(1 + 2\,a/b)$$

where f is the tensile stress applied at the ends of the plate. This stress increases with the ratio a/b, so that a very narrow hole perpendicular to the direction of tension produces a very high stress concentration." The above reference gives no indication that the stress concentration factor might vary with the ratio of the width of opening to the width of the plate. This is a summary of the meager information available on the problem.

The problem was not only the one of determining the stress concentration factors for the three types of openings suggested, but also of determining the variation of the factor for multiple openings of each type with varying depths of pillars between. A theoretical analysis would not only be extremely complex, but would be of doubtful practical value. From the practical stand-point there were two methods available for investigation of the problem: photoelasticity and brittle lacquer. Strain gages would only give an average value of strain over the gage length. This could cause an appreciable and indeterminate error even over a 1/8 inch gage length. Several factors favored the use of brittle lacquer. Many tests could be run in the limited time available. The technique is fairly new and does not require extensive preparation. It was felt that the results could be checked by the photoelastic method if time permitted.

The Navy Department wished to obtain the stress concentration factors for plates subject to a uniform compressive

load. There were many difficulties, however, which would be encountered in the use of brittle lacquer in testing compression loads. The plates would have to be coated under load, then allowed to dry and the load released. Such a procedure would be extremely cumbersome with the equipment available. Since the load would be uni-axial in any case, the investigation was conducted with tension loads. The factors will, of course, be identical for both tension and compression loads.

During the course of the experiment the investigation was carried out in three principal parts. The first part consisted of tests using moderate oven temperatures for drying; the second part, drying in air; the third part, using higher temperatures in conjunction with another research project.

PREPARATION OF MATERIALS

After having determined the number and type of openings to be tested, the investigators were faced with the problem of determining the material and dimensions of the specimens and the design and construction of the necessary apparatus for testing the specimens. The material to be used for the specimens should have two properties: it should have a low modulus of elasticity to yield a maximum strain with the least stress, thus reducing the load required to fracture the lacquer; and it must have a sufficiently high yield point to sustain strains of at least five times that required to fracture the lacquer without yielding. This is necessary in order to examine the strains over the entire plate without causing local yielding around the openings. The material which best fulfilled these qualifications was 24 ST aluminum, which has a modulus of 10,300,000 psi and a tensile strength of 44,000 psi.

The thickness of the plate should be the smallest which would allow handling and working without warping. The investigators decided to use 1/8" plate for the tests. However, since this was not available, 3/16" plate was substituted.

The relative dimensions of the plates and openings as prescribed by the Bureau of Yards and Docks are as follows:

Circular openings--$r/h = 1/15$ or $1/20$ where r is radius of opening and h is depth of plate.

Half-elliptical openings--$a/h = c/2h = 1/15$ or $1/20$ where a is minor intercept and c is major intercept.

Bi-elliptical openings--same as semi-elliptical openings but with bottom minor intercept of $a/3$.

The selection of the proper scale was very important for the proper interpretation of results. In determining the actual dimensions of the openings, the investigators felt that the minimum depth of opening should be 3/4" to facilitate fabrication of the samples and examination of the lacquer during testing. This depth of opening would require a clear depth of plate between 11.25" and 15". The maximum width of any opening would then be 3". In order to test two or more openings with varying depths between, the width of the plate must be about 16" to 18". Actually 3/4" was used for the a and r dimensions indicated above. The clear depth of plate was about 13" and the width about 16" or 18".

The fabrication of the circular holes presented no difficulties. The holes were drilled and reamed to size. The edges of the holes were polished to remove the rim left by the reaming operation, then checked to make sure the edges of the holes were perpendicular to the faces of the plates. Care was taken to insure that all holes had sharp, square

edges without any overhang or rounding.

The semi-elliptical and bi-elliptical holes presented a considerable fabrication problem. There was neither time nor facilities available to obtain dies to punch the openings. The only solution seemed to be to drill and file the openings to proper size. The pattern was made by scribing a perfect ellipse on a plate using two pins and a taut cord. This plate was then used as a pattern for the other openings to insure uniformity. While this was a very tedious procedure, the openings were very carefully made to the precision desired. The edges were carefully filed to right angles and the corners were filed to the exact contour desired. All corners and edges were then polished smooth with emery cloth. It was felt that this was largely responsible for the uniformity of the results obtained.

The openings tested are illustrated on Figure I. Besides the tests of single openings of the relative dimensions illustrated, tests were made using plates with the following combinations of openings:

1. three circular openings 3" o.c.
2. two semi-elliptical openings 5", 6" and 7" o.c.
3. two bi-elliptical openings 5", 6" and 7" o.c.

It was hoped that the experiments would illustrate any variation in stress concentration factor with variation in pillar depth.

The load to be sustained by the testing jig was computed as follows:

Average minimum strain to fracture lacquer--0.001 in./in.
Average stress in gross cross-section of plate--
0.001 x 10,300,000 = 10,300 psi.
Gross area of plate--3/16 x 18 = 3.37 sq. in.
Total load--3.37 x 10,300 = 34,700 lbs.

The jig was then designed to apply this load uniformly over an 18" length without appreciable deflection. The plans for this jig are included in this paper. The load was transmitted from the jig to the plates through $\frac{1}{2}$" chrome steel pins fitted in machined holes $1\frac{1}{2}$ o.c. This jig proved highly satisfactory throughout the experiments.

INVESTIGATION USING MODERATE OVEN TEMPERATURES FOR DRYING

On the advice of Prof. R. H. Trathen, the first three tests were made using the oven-drying technique which was concurrently being investigated by J. H. Wilson and B. T. Dibble. This technique was expected to give much greater sensitivity than that obtained by the usual method of air-drying the lacquer.

In this phase of the investigation the conventional method of determining and applying the proper lacquer was used. The plates and calibration bars were first coated with aluminum undercoating for all runs.

The optimum lacquer for the spraying conditions was then applied to the plates. For the first run the entire depth of the plates was sprayed to test the jig for uniform load across the edge of the plate. For the other runs the plates were sprayed only around the openings. The plates and calibration bars were then placed in the oven at the temperatures indicated. The usual steel calibration bars were used for calibrating.

After drying, the plates and calibration bars were removed from the oven and placed in the laboratory near the testing machine. At least twenty minutes elapsed before testing any plate to insure cooling to room temperature. The temperature in the laboratory during testing was recorded.

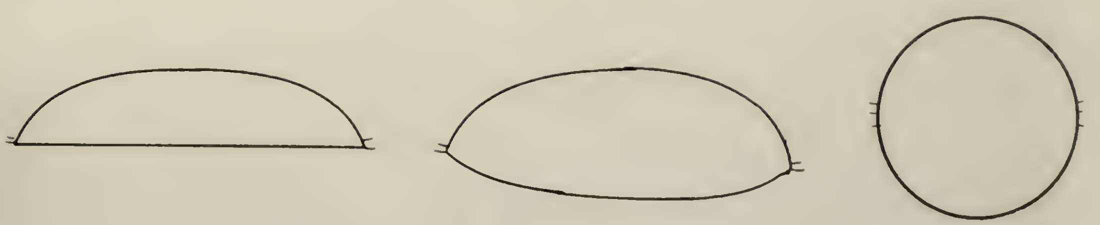
The tests were made in a Southwark-Emery 100,000 lb. testing machine. The procedure used during testing was as follows:

A plate was inserted in the testing jig and all pins were inserted in the holes. The plate was carefully examined for crazing or cracks caused by driving the pins. An observer was stationed on each side of the plate and load was applied. A stop watch was used to clock the time from the beginning of application of load until the first cracks appeared. The time and load of the first cracks were recorded. The plate was then examined without further increase in load, and any irregularities were noted.

After examination, more load was applied in varying increments on the first run to obtain stress patterns over the whole plate. By carefully watching the lacquer at some distance from the openings it was determined that cracks appeared over the entire width of the plate at the same load. This indicated that the load was being applied uniformly at the edges, at least within the accuracy of the brittle lacquer. Photographs of the stress patterns obtained from the first run are included in a later section.

At the openings cracks would usually appear at all corners simultaneously, or nearly so. Sometimes there would be only one crack at a corner, but usually there would be two or three cracks at the first fracture. These cracks were about 1/8" long. Their locations with respect to the

corners for the various types of openings are indicated in the sketches below.



The stress concentration factors were determined from the data as follows:

The calibration strain was corrected for creep during the time of loading using the creep correction curve reproduced herein as Figure 3. This corrected strain was then multiplied by the modulus of elasticity--10,300,000 psi.--to obtain the stress at the point where the cracks occurred. The average stress over the net area of the plate was found by dividing the load on the plate at the time of the first cracks by the net area of the plate. The ratio of the stress at the cracks to the average stress is the stress concentration factor. The factors for the first three runs were then tabulated and examined.

At this point in the investigation it became apparent that the results were very low and erratic. After much deliberation it was finally decided that the procedure of using steel calibration bars and aluminum samples was decidedly faulty. Upon investigation it was determined that the linear coefficient of thermal expansion for steel was

sections for the various types of openings are indicated in the sketches below.

The stress concentration factors were determined from the data as follows:

The calibration strain was corrected for creep during the time of loading using the creep plotted on curve reproduced mainly as Figure 8. This corrected strain was then multiplied by the modulus of elasticity—10,000,000 psi.—to obtain the stress at the point where the strain occurred. The average stress over the net area of the plate was found by dividing the load on the plate at the time of the first reading by the net area of the plate. The ratio of the stress at the crack to the average stress is the stress concentration factor. The results for the first three runs were then tabulated and analyzed.

At this point in the investigation it became apparent that the results were very low and erratic. After some deliberation it was finally decided that the procedure of using these calibration bars was at fault. [illegible] Upon investigation it was determined that the linear coefficient of thermal expansion of steel was

approximately 0.0000065/$^{\circ}$F. as compared to about 0.000013/$^{\circ}$F. for the aluminum. The effect of this difference was as follows:

After spraying, the plates and calibration bars were placed in the oven while the lacquer was in a plastic condition. During the drying period the temperature was maintained constant. Upon removing the plates and bars from the oven, however, the aluminum plates would contract much more than the steel bars. This would have the effect of placing an initial compression in the lacquer on the aluminum plates corresponding to the difference in contraction between the aluminum and the steel. This compression effect would be maintained until the plate was loaded in tension. During this time, however, the effect would be somewhat reduced by creep in the lacquer. Upon loading the plate, a greater strain would then be required to fracture the lacquer. During the time the load was being applied creep would again take place in the lacquer, this time in the opposite direction. The net effect of creep would thus be rather uncertain.

The correction to compensate for this error was made quite simply. The difference in the linear coefficients of thermal expansion of the two materials was taken as 0.0000065/$^{\circ}$F. The difference in contractions between the two materials was this value multiplied by the temperature difference between the oven and the laboratory. This was the difference in strain induced in the lacquer by the

unequal contractions of the materials. Creep was considered negligible as far as this strain was concerned. It was reasoned that whereas the time during which creep would take place to relieve the compression in the lacquer was considerably greater than that during which it would act to relieve the tension strain, since the tension strain would be much higher the net result would be unappreciable. The correction to be made was thus only the stress corresponding to the difference in contractions. This correction was applied to the creep-corrected calibration stress to obtain the actual stress at which the lacquer fractured. This procedure produced results which compared very favorably with those obtained using air-drying in the second phase of the investigation. Whereas there were certain errors in this procedure which were indeterminate, it was felt that they were of such small magnitude as not to affect the final result materially.

INVESTIGATION USING AIR DRYING

After consideration of the somewhat uncertain results of the first part of the investigation, the investigators decided to make several runs drying the plates in the conventional manner. The plates were coated with lacquer in the usual way, then dried at room temperature over night. The testing procedure was the same as for the previous runs.

Four runs were made in this manner, numbered 4 through 7. It was found that the calibration strains were considerably higher, but that the value of the factors did not vary beyond experimental limits. The dispersion was approximately the same as for the first three runs.

The reduced sensitivity of the lacquer when dried in air was not an inconvenience in this investigation. In fact, it may be that the results are slightly more accurate. Since the loads were higher, a small error in reading or calibration would have less effect on the factor.

This part of the investigation served mainly as a check on the first part and to obtain additional values to compute the mean factors. The results compared favorably with those obtained in the first three runs.

THE USE OF HIGHER TEMPERATURES IN CONJUNCTION WITH ANOTHER RESEARCH PROJECT

The next three runs, numbers 8, 9, and 10, were carried on in conjunction with a contemporary research project on the heat treatment of brittle lacquer by Lieutenants (junior grade) B. T. Dibble and J. S. Wilson, Civil Engineer Corps, U. S. Navy at R.P.I. These officers investigated the use of heat treatment to sensitize the lacquer and had at this time obtained sets of optimum conditions of lacquer numbers with corresponding degrees of heat treatment. It was desired to test these conditions of heat treatment on the complicated shapes and the practical problem of this stress concentration project. As indicated in runs 1, 2, and 3 of this project the Dibble-Wilson heat treatment of the test plates was used but at that early date a final set of optimum conditions had not been obtained and the investigation of this project showed a return to the standard method of air drying would be advisable.

Three sets of optimum conditions as suggested by Dibble and Wilson were set up for the same group of plates. The plates were sprayed, heat treated and tested with a run for each of the three sets of conditions. These runs are the following runs designated as numbers 8, 9, and 10.

Run #8 consisted of plates, 1, 2, 3, and 4, the semi-ellipse group, sprayed with lacquer number 1205, heat treated for 28 hours in the oven at 124°F., and slowly cooled to room temperature. Run #9 consisted of the same set of plates but with lacquer #1201 and oven temperature of 168°F. Run #10 was with same plates using lacquer #1203 and oven temperature 148°F.

These three seperate runs served to confirm the Dibble-Wilson conclusions of increased sensitivity with heat treatment which will undoubtedly be a tremendous stride in the success of brittle lacquers. However, this increased sensitivity for this one particular project on stress concentrations did not materially aid in the determinations of the factors. In run #8 the lacquer was so sensitive that the impact of driving the pins to set the plate in the jig produced small cracks at the critical points of the openings which again was proof of the increased sensitivity but which was undesirable for this project in that the resulting stress concentration factor for each plate in each run hinged on the accurate observation of the first minute crack in the lacquer under load.

The second apparent disadvantage of using heat treatment for this project was the necessity of using a calculated correction for the difference in coefficients of expansion between the aluminum test plates and the steel calibration strips. This calculated temperature correction stress at the

high oven temperature runs far outweighed the stress for the calibrated strain which was undesirable. For example, in run #9 the temperature correction amounted to 6170 psi while the stress obtained from the creep corrected calibration bar strain was only 3040 psi. An attempt was made to eliminate the necessity of this correction by the preparation of aluminum calibration strips, however the aluminum strips were of insufficient strength to withstand the deflection of the calibrator cam and all bars were permanently deformed. Had there been time available a new cam for the calibrator could have been prepared to give a much smaller deflection, therefore allowing the use of aluminum. Another possible remedy would have been to use calibration strips of 75 ST aluminum which has a yield strength of approximately 80,000 psi and could have withstood the deflection. Again the unavailability of materials and lack of time prevented this refinement.

A third disadvantage of these high heat treatments was the wide dispersion of results obtained as noted in the data for the three runs.

CONCLUSIONS

The average values for the stress concentration factors and the maximum dispersions for the ten plates tested are tabulated below.

	Factor	Dispersion
Plate 1--single semi-ellipse	3.23	24.7%
2--two semi-ellipses 5" o.c.	2.60	18.5%
3--two semi-ellipses 6" o.c.	2.66	12.0%
4--two semi-ellipses 7" o.c.	3.04	15.5%
5--single bi-ellipse	3.28	20.5%
6--two bi-ellipses 5" o.c.	2.54	18.5%
7--two bi-ellipses 6" o.c.	2.63	25.0%
8--two bi-ellipses 7" o.c.	2.80	19.0%
9--single circular hole	1.94	11.3%
10--three circular holes 3" o.c.	1.82	20.3%

The conclusions which the authors have drawn from the above results and the experiment as a whole are as follows:

(1) brittle lacquer is an excellent means for determining stress patterns in plates with openings.

(2) brittle lacquer is an excellent means for locating points of stress concentration.

(3) the dispersion may be as great as 25%, with occasional errors of much greater magnitude.

(4) the stress concentration factors obtained by the use of the brittle lacquer technique are definitely lower than theoretical values or other available experimental values. For instance, the graph on page 3 gives a factor of about 2.6 for the opening in plate #9 as compared to an average value of 1.94 obtained by the brittle lacquer technique. It is believed that the factors for the elliptical openings are considerably lower than theoretical.

(5) the tests showed that there was no noticeable variation in factors in the inside and outside corners of the openings in a plate.

(6) there is no appreciable difference between the factors for semi-ellipses and bi-ellipses.

(7) the factors seemed to vary according to this rule: a single opening causes the highest factor. For two openings the factor increases with the distance between the openings. For the openings tested all the factors for two openings were less than those for one. It seems likely that the factor for two openings would approach that for one opening as the distance between openings increases, but this was not definitely determined.

(8) the shape of the stress pattern is affected by the curvature of the opening. Comparing figures 7, 13, and 14, one can see that as the curvature increases the isoentatic moves outward from the curved portion of the opening. This effect is most noticeable on Figure 7, the semi-ellipse. The isoentatics in this case are extended much farther above the curved portion than below the straight bottom of the opening. A study of this phenomenon was outside the scope of this investigation. Such a study might, however, throw considerable light on the effect of openings in plates.

The reason for the low values of stress concentration factors has not been determined. One possible solution is that the lacquer was thin over the edges of the openings and would therefore not fracture at as low a strain as the lacquer on the calibration bars. However, every possible means was taken to obtain a uniform thickness of lacquer at all points around the opening. The investigators are of the opinion that this did not have an appreciable effect on the factors obtained, but was mentioned merely to caution other investigators to use great care in applying the lacquer around openings.

Another possible cause of the low values obtained was the discontinuity of the lacquer near the edges of the openings. As far as can be determined from observing carefully the cracks on calibration bars it seemed that lacquer cracked at the edges of the bars at the same strain as in the body of the lacquer itself. However, this has not been thoroughly investigated and no definite statements can be made concerning it.

The great difficulty in this work is that the stress drops off so rapidly near the opening that a value obtained at only a minute distance from the opening would be considerably in error. As far as could be determined the stresses obtained in this investigation were the correct values, but perhaps there was some source of error at this critical point which has not as yet been recognised. It was felt that this is a particularly important phase of the use of brittle lacquer and would be a worthwhile problem for future investigation.

Any readers making a comparison of these factors with others are cautioned that these factors are based on the net area and not on gross area. Factors based on net area will be smaller than factors based on gross area.

SUGGESTIONS FOR FUTURE INVESTIGATION

The following suggestions for future investigation are set down by the authors:

(1) The investigation of stress concentration factors for plates in compression might yield valuable information about the problem. Such an investigation would require special equipment and considerable time. The method of spraying while plate is under a compressive load, drying under load, and testing by relaxing load could be used.

(2) An investigation using a jig which would clamp the plates would eliminate some of the troubles experienced from driving the pins in this investigation, therefore the increased sensitivity of heat treatment could be used.

(3) The development of a technique which would guarantee a uniform thickness of lacquer inside and at the edges of the openings would probably yield more reliable results than the usual technique. A finer lower pressure spray or perhaps a brush could be used.

(4) A study of the variation of stress concentration factors over a wider range of pillar depths would be of great value.

(5) An investigation of the same openings using the photoelastic technique would be a valuable check on the results obtained.

(6) In association with heat treatment the preparation of calibration strips of the same material as the test plates with possible pre-requisite preparation of a calibrator cam to give small deflections would eliminate the need of the large thermal expansion corrections that were necessary in this particular experiment. Or the preparation of calibration strips of 75 ST aluminum to withstand the deflection of the calibrator cam could likewise be done for use with aluminum plates.

DESCRIPTIONS OF TEST PLATES

Plate No.	Average Thickness	Gross Width	Net Width	Gross Area	Net Area
1	0.1870	15.88	12.75	2.97	2.39
2	0.1870	15.88	9.75	2.97	1.62
3	0.1880	15.88	9.81	2.90	1.84
4	0.1865	18.06	11.94	3.37	2.23
5	0.1865	15.88	12.81	2.96	2.39
6	0.1880	15.88	9.91	2.90	1.86
7	0.1885	18.06	12.00	3.41	2.27
8	0.1870	18.00	11.94	3.37	2.23
9	0.1870	15.88	14.38	2.97	2.69
10	0.1885	15.88	11.38	3.00	2.15

Plate No. 1 has one Semi-ellipse, centered

Plate No. 2 has two Semi-ellipses, 5"o.c.

Plate No. 3 has two Semi-ellipses, 6"o.c.

Plate No. 4 has two Semi-ellipses, 7"o.c.

Plate No. 5 has one Bi-ellipse, centered

Plate No. 6 has two Bi-ellipses, 5"o.c.

Plate No. 7 has two Bi-ellipses, 6"o.c.

Plate No. 8 has two Bi-ellipses, 7"o.c.

Plate No. 9 has one Circle, centered

Plate No. 10 has three Circles, 3"o.c.

OBSERVED DATA

Run #1 July [illegible], 1948

All plates coated with #1207; dried [illegible]0 hours in oven at 90°F. Room temperature during test 70°F.

Calibrations: 6.61, 5.57 average 6.09×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Corrected* Stress at Cracks	Factor
1	7550	1320	3160	10,940	3.47
2	4230	1140	4230	10,840	2.57
3	6500	80	3520	8780	2.49
4	7500	70	3370	8670	2.57
5	10,500	270	2510	8360	3.33
6	8000	90	4300	8880	2.07
7	10,000	150	4420	8980	2.03
8	8500	90	3800	8880	2.33
9	10,600	60	3950	8550	2.16
10	4000	30	1860	8370	4.48

* Corrected stress includes the following corrections:

(1) for difference in coefficients of thermal expansion of steel calibration strip and aluminum test plates during cooling from 90°F. (oven temperature) to 70°F. (room temperature).

$$\text{Correction} = 65 \times 10^{-7} \times 10.3 \times 10^{6} \times 20 = 1340 \text{ psi}$$

(2) for creep during time of test, obtained from creep curves.

Sample: Plate No. 1.

Calibration strain is 6.09×10^{-4} inches/inch.
Strain corrected for creep during 1320 seconds is 9.30×10^{-4} inches/inch.
Corresponding stress $9.30 \times 10^{-4} \times 10.3 \times 10^{6} = 9600$ psi
Stress corrected for temperature $= 9600 + 1340 = 10,940$ psi.

OBSERVED DATA

Run #2 July 29, 1948

All plates coated with #1207; dried 20 hours in oven at 110°F. Room temperature 77°F.

Calibrations: 2.08, 3.08 average 2.58×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Corrected* Stress at Cracks	Factor
1	6400	150	2680	5590	2.07
2	2500	5	1370	4910	3.58
3	2400	45	1310	5010	3.83
4	3500	60	1570	5350	3.41
5	4200	60	1750	5350	3.05
6	2500	75	1345	5400	4.01
7	5000	50	2190	5020	2.29
8	4000	150	1790	5590	3.11
9	No readings -- badly crazed.				
10	4500	30	2090	5220	2.50

* See Run #1

OBSERVED DATA

Run #3 July 29, 1948

All plates coated with #1208; dried 20 hours in oven at 100°F.
Room temperature 80°F.

Calibrations: 3.1, 3.6 average 3.35×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Corrected* Stress at Cracks	Factor
1	3900	15	1630	5140	3.15
2	4600	36	2520	5280	2.12
3	3400	20	1840	5180	2.88
4	2300	8	1030	5020	4.88
5	3200	9	1330	5020	3.77
6	3800	25	2040	5210	2.56
7	4000	17	1760	5140	2.93
8	4400	35	1960	5320	2.72
9	5300	10	1960	5070	2.06
10	5600	30	2600	5280	2.02

* See Run #1

OBSERVED DATA

Run #4 August 3, 1948

All plates coated with #1208; dried 26 hours at room temperature.

Calibrations: 5.8, 6.1 average 5.95×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Stress at Cracks	Factor
1	5100	19	2130	6800	3.18
2	4600	22	2520	6870	2.72
3	5200	10	2820	6620	2.34
4	5800	23	2600	6870	2.63
5	5150	25	2160	6870	3.16
6	5040	25	2720	6870	2.52
7	6200	32	2720	6380	2.34
8	6000	28	2690	6300	2.34
9	10,800	42	4020	7110	1.77
10	9800	12	4560	6620	1.45

OBSERVED DATA

Run #5 August 6, 1948

All plates coated with #1206; dried 17 hours at room temperature.

Calibration: 7.32×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Stress at Cracks	Factor
1	8500	60	3570	8900	2.49
2	6100	14	3350	8210	2.45
3	5600	22	3040	8450	2.78
4	7100	60	3180	8900	2.80
5	8100	60	3400	8900	2.61
6	5800	25	3110	8450	2.71
7	6700	23	2940	8450	2.87
8	6100	20	2740	8390	3.05
9	14,000	66	5210	9000	1.72
10	11,200	22	5220	8450	1.61

OBSERVED DATA

Run #6 August 7, 1948

All plates coated with #1206; dried 26 hours at room temperature.

Calibration: 8×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress Net Area	Stress at Cracks	Factor
1	6100	32	2550	9410	3.70
2	6000	26	3220	9270	2.87
3	6200	31	3370	9350	2.77
4	6300	30	2830	9300	3.30
5	6400	22	2670	9270	3.45
6	7100	31	3820	9350	2.44
7	8000	24	3520	9270	2.63
8	6100	18	2720	9090	3.33
9	13,100	50	4880	9670	1.98
10	9200	30	4270	9300	2.18

OBSERVED DATA

Run #7 August 10, 1948

All plates coated with #1205; dried 28 hours at room temperature.

Calibration: 8.26×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Stress at Cracks	Factor
1	5800	25	2420	8150	3.37
2	5100	21	2800	8120	2.90
3	6100	30	3310	8300	2.49
4	5100	20	2280	8090	3.51
5	5400	19	2250	8090	3.58
6	5100	19	2740	8090	2.94
7	5600	21	2460	8120	3.29
8	6800	32	3040	8300	2.73
9	6600	29	2450	8300	3.38
10	9800	48	4560	8450	1.85

OBSERVED DATA

Run #8 August 12, 1948

Plates 1, 2, 3, and 4 coated with #1205; heat treated at 124°F. for 28 hours. Room temperature 78°F.

Calibration: 2.0×10^{-4}

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Corrected* Stress at Cracks	Factor
1	3000	9	1250	5290	4.23
2	3500	17	1920	5350	2.78
3	4200	27	2280	5410	2.37
4	2800	9	1270	5290	4.16

* See Run #1

OBSERVED DATA

Run #9 August 17, 1948

Plates 1 to 4 coated with #1201; heat treated 20 hours in oven at 168°F. Cooled in oven to room temperature 76°F.

Calibration: 2.7×10^{-4} inches/inch

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Corrected* Stress at Cracks	Factor
1	2600	13	1090	9210	8.47
2	3000	16	1650	9240	5.60
3	2000	8	1080	9150	8.48
4	3000	21	1340	9280	6.92

* See Run #1

OBSERVED DATA

Run #10 August 18, 1948

Plates 1 to 4 coated with #1203; heat treated 20 hours in oven at 148°F. Cooled in oven to room temperature of 76°F.

Calibration: 4.6 x 10^{-4} inches/inch

Plate	Load to Reading	Time Sec.	Average Stress-Net Area	Corrected* Stress at Cracks	Factor
1	4900	31	2050	10,230	5.00
2	5300	20	2920	10,100	3.47
3	5000	22	2720	10,140	3.71
4	4400	32	1970	10,230	5.20

* See Run #1

COMPUTATION AND COMPARISONS OF FINAL FACTORS

	Runs								
Plate	I	II	III	IV	V	VI	VII	Total	Average
1	3.47	2.07*	3.15	3.18	2.49	3.70	3.37	19.36	3.23
2	2.57	3.58*	2.12	2.72	2.45	2.87	2.90	15.63	2.60
3	2.69	3.83*	2.88	2.34	2.78	2.77	2.49	15.95	2.66
4	2.57	3.41	4.88*	2.63	2.80	3.30	3.51	18.22	3.04
5	3.33	3.05	3.77	3.16	2.61	3.45	3.58	22.95	3.28
6	2.07	4.01*	2.56	2.52	2.71	2.44	2.94	15.24	2.54
7	2.03	2.29	2.93	2.34	2.87	2.63	3.29	18.38	2.63
8	2.33	3.11	2.72	2.34	3.05	3.33	2.73	19.61	2.80
9	2.16	----	2.06	1.77	1.72	1.98	3.38*	9.69	1.94
10	4.48*	2.50*	2.02	1.45	1.61	2.18	1.85	9.11	1.82
Total (1-8)	21.06	11.86	20.13	21.23	21.76	24.39	24.61		
Ave.	2.63	2.96	2.88	2.65	2.72	3.05	3.08		

* This value arbitrarily discarded as it differed from the mean for the plate by more than twenty-five per cent.

EXPLANATION OF PHOTOGRAPHS ON FOLLOWING PAGES

Some of the following photographs were made of the test plates after a test run. A red dye etchant was used to accentuate the small cracks for better photographing purposes.

The photographs are primarily to show the stress distribution over the area surrounding the openings. For the actual calculation of the concentration factors only the first minute crack was necessary but the crack was too small to be photographed. Some photographs show the isoentatics for various loads and some clearer photographs show the isostatics. An isoentatic is a line drawn to join the ends of the cracks (isostatics) in the lacquer, thus is the locus of points of equal strain. An isostatic is an actual crack in the lacquer or the lines of failure of the coating. The directions of the principal stresses are tangent and perpendicular to the isostatics.[1] See Figure 14 for procedure for obtaining isoentatics.

1. A. J. Durelli, "What Kind of Information Does Brittle Lacquer Give", Product Engineering, June, 1948.

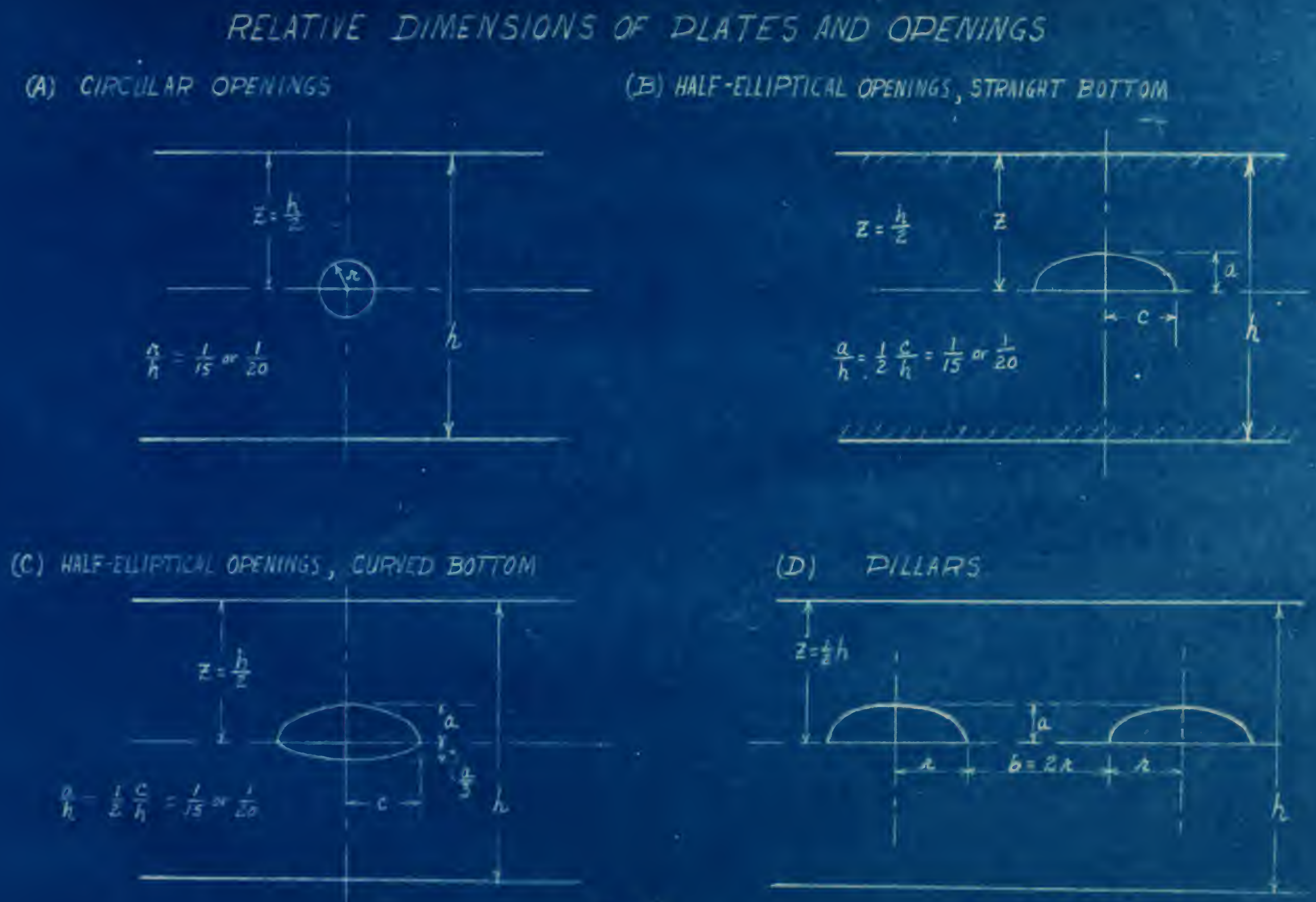
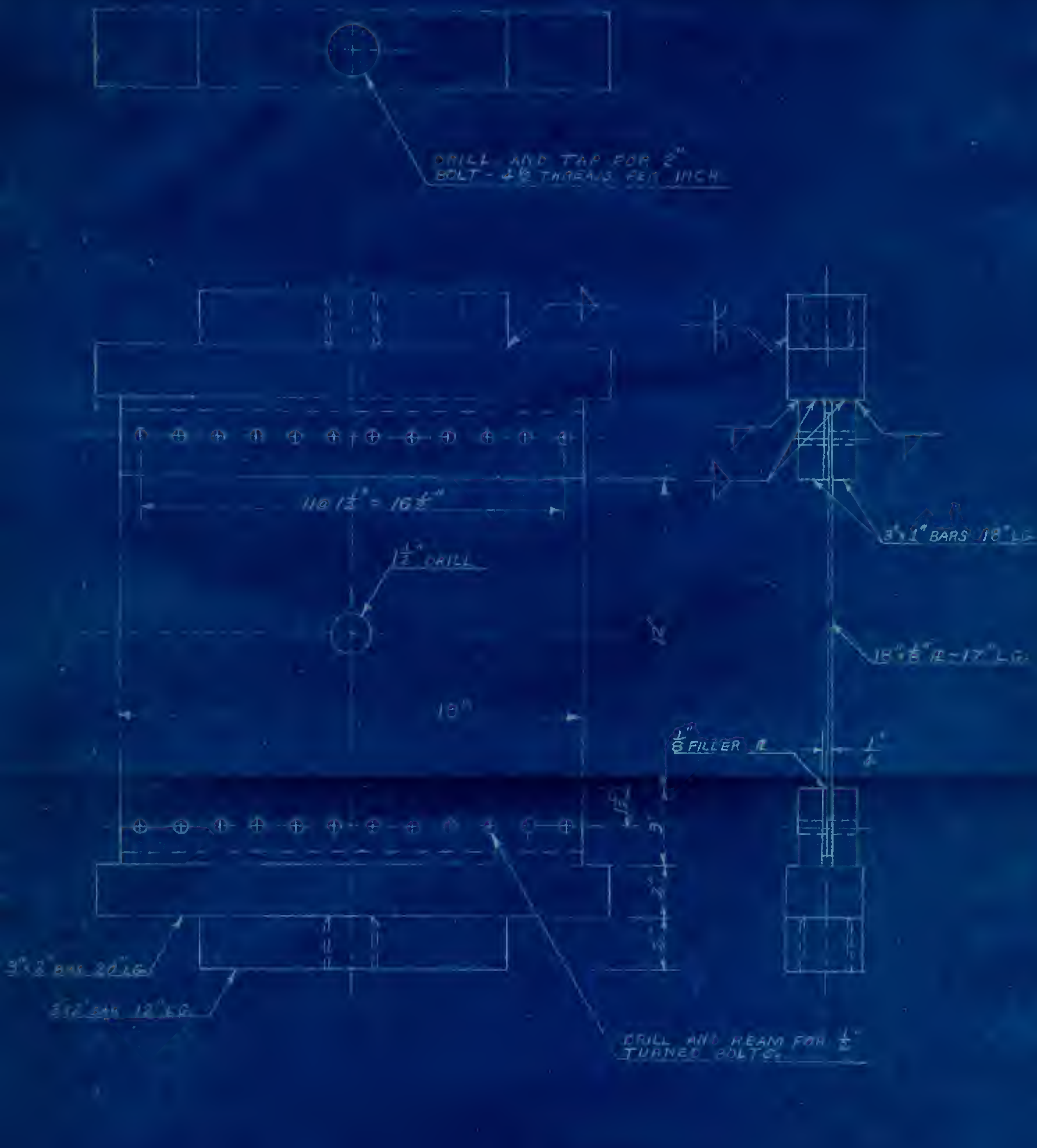

RELATIVE DIMENSIONS OF PLATES AND OPENINGS
(A) CIRCULAR OPENINGS
$z = \frac{h}{2}$
r
h
$\frac{r}{h} = \frac{1}{15}$ or $\frac{1}{20}$
(B) HALF-ELLIPTICAL OPENINGS, STRAIGHT BOTTOM
$z = \frac{h}{2}$
z
a
c
h
$\frac{a}{h} = \frac{1}{2}\frac{c}{h} = \frac{1}{15}$ or $\frac{1}{20}$
(C) HALF-ELLIPTICAL OPENINGS, CURVED BOTTOM
$z = \frac{h}{2}$
a
$\frac{a}{3}$
c
h
$\frac{a}{h} = \frac{1}{2}\frac{c}{h} = \frac{1}{15}$ or $\frac{1}{20}$
(D) PILLARS
$z = \frac{1}{2}h$
a
r
$b = 2r$
r
h

FIG. 1



NOTES:

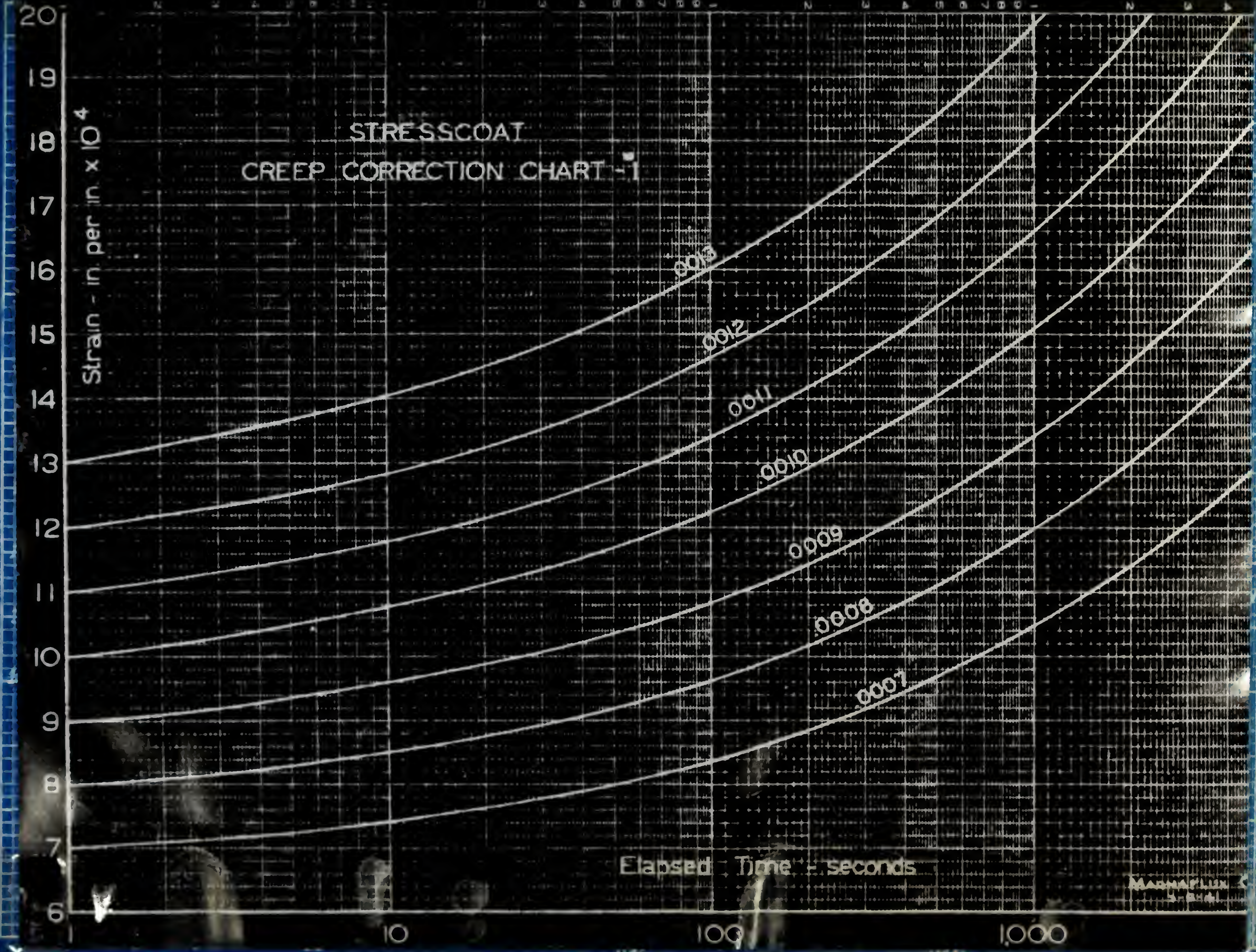
ALL WELDS TO BE ¼".

½" HOLES TO BE DRILLED WITH ALL PIECES ASSEMBLED AND SECURELY CLAMPED. ½" HOLES TO BE DRILLED BEFORE 2" HOLES ARE DRILLED.

CENTER LINES OF 2" HOLES MUST BE COINCIDENT, WITH PIECES ASSEMBLED, WITHIN .003".

TEST SUPPORT DETAILS	
D.K. MARQUARDT	A.S. WATERS
RENSSELAER POLYTECHNIC INSTITUTE	
SCALE:	DATE
1" = 4"	MAY 1, 1948

FIG 2



STRESSCOAT
CREEP CORRECTION CHART - 1
Strain - in per in x 10^4
Elapsed Time - seconds
.0013
.0012
.0011
.0010
.0009
.0008
.0007
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
1
10
100
1,000

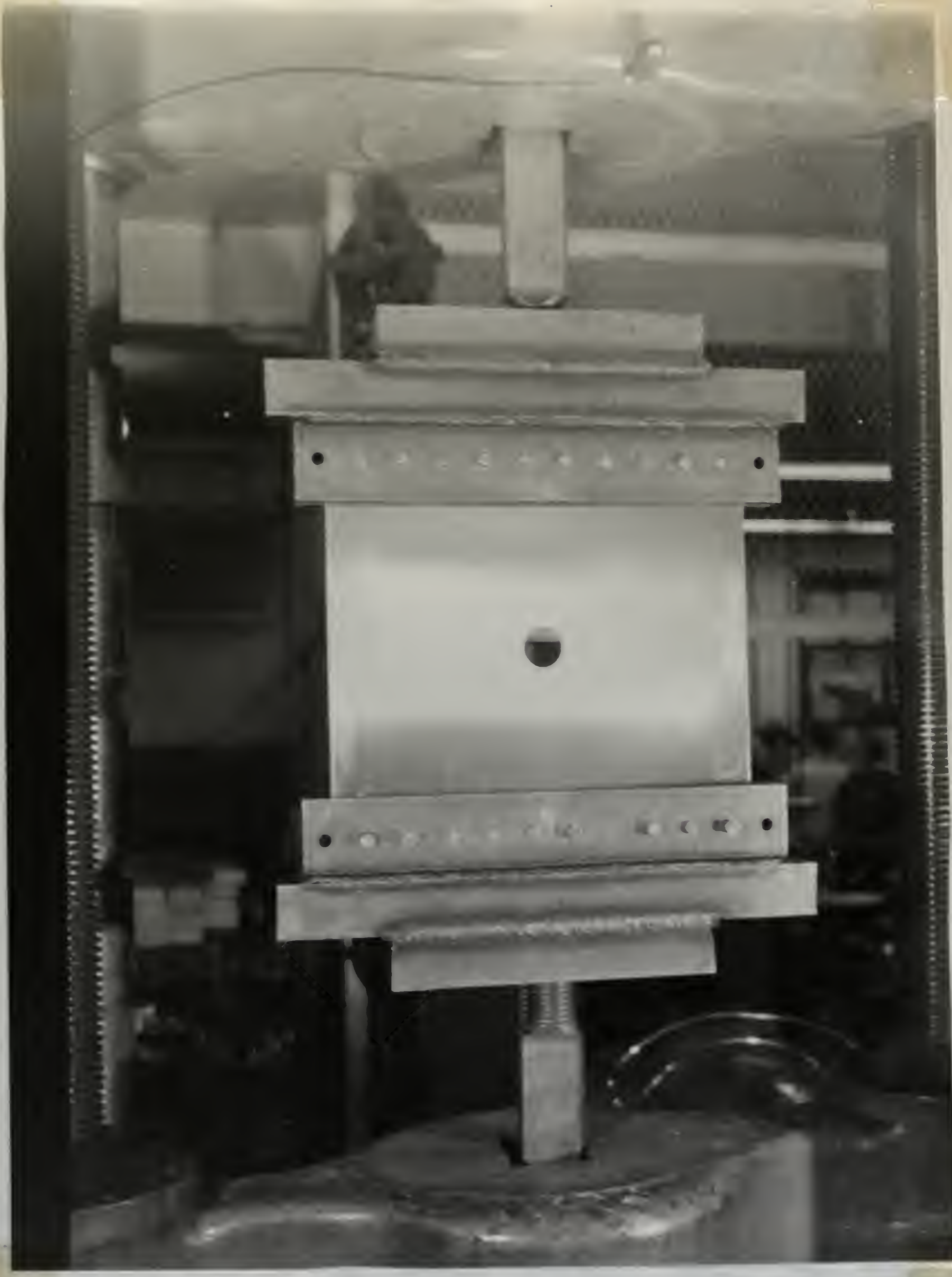


Fig. 4
This is a photograph of the apparatus set for a test run. It shows a front view of the jigs and the large bolt leading to the cross heads of the testing machine. Plate #9 is shown mounted in the jig. The wide light colored band across the center of the plate is the dried coating of lacquer.

Fig. 5

Side view of jig with plate mounted.

Fig. 6

Close-up view of semi-ellipse of plate #1 after test run showing isostatics. An isostatic is a line of failure of the coating. Cracks first appeared at the corners and as the load was increased the cracks gradually appeared over whole plate.

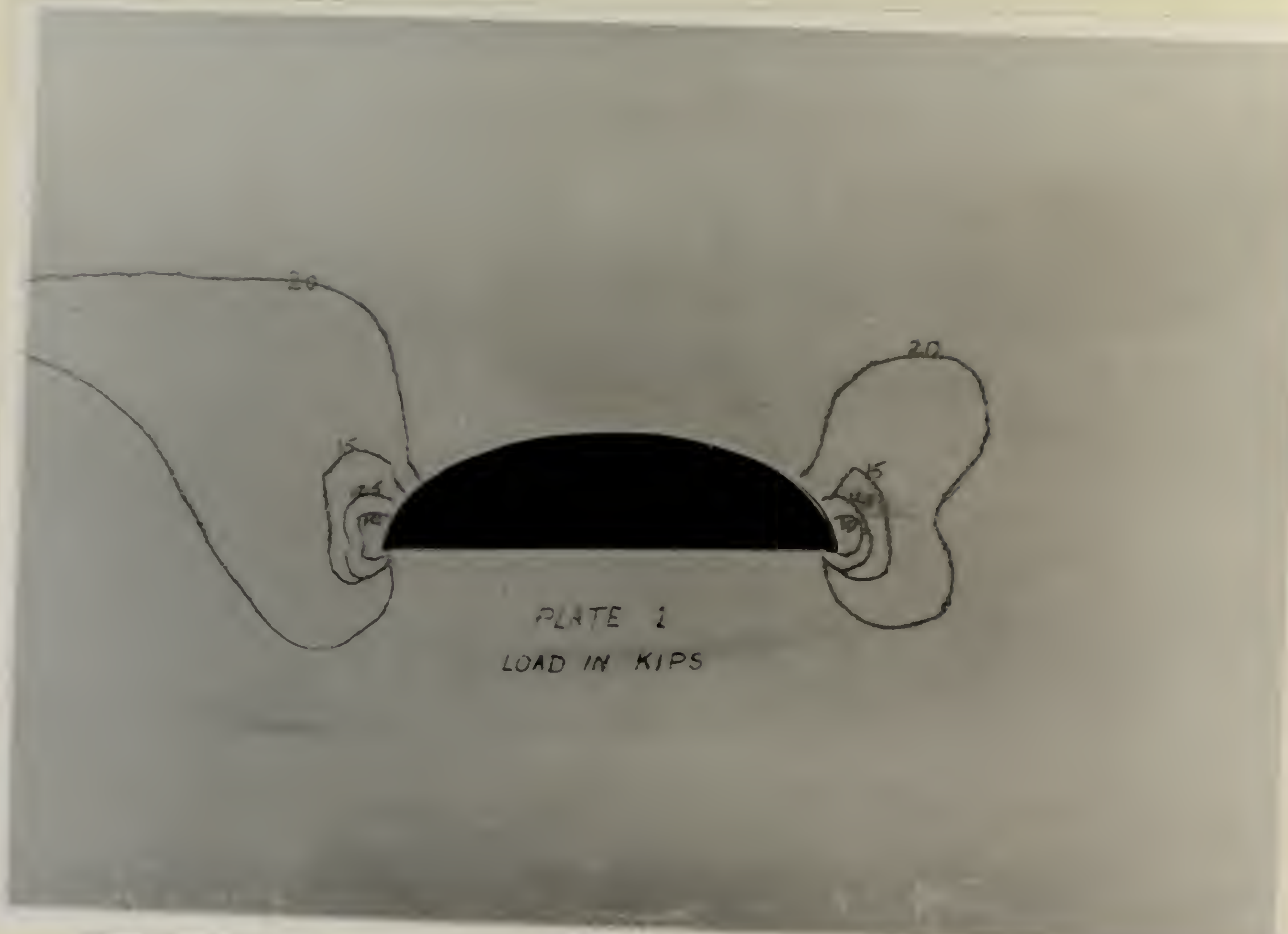


Fig. 7

Plate 1 with isoentatics for loads of 10 kips, 12.5 kips, 15 kips and 20 kips. The isostatics are easily seen in the large 20 kips loop to the left. This loop was probably due to an unequal pull on this particular test run or possibly due to a weak area in the plate in that region.

Fig. 8

Plate 1, showing close up view of isoentatics for loads 1.5 kips to 3.0 kips.

Fig. 9

Plate 2 with isoentatics for loads 7.5 kips to 30 kips.

Fig. 10

Close-up view of plate #5 showing isoentatics for loads 5 kips, 7.5 kips, 10 kips and 15 kips. Isostatics may also be seen in the large loop to the left.

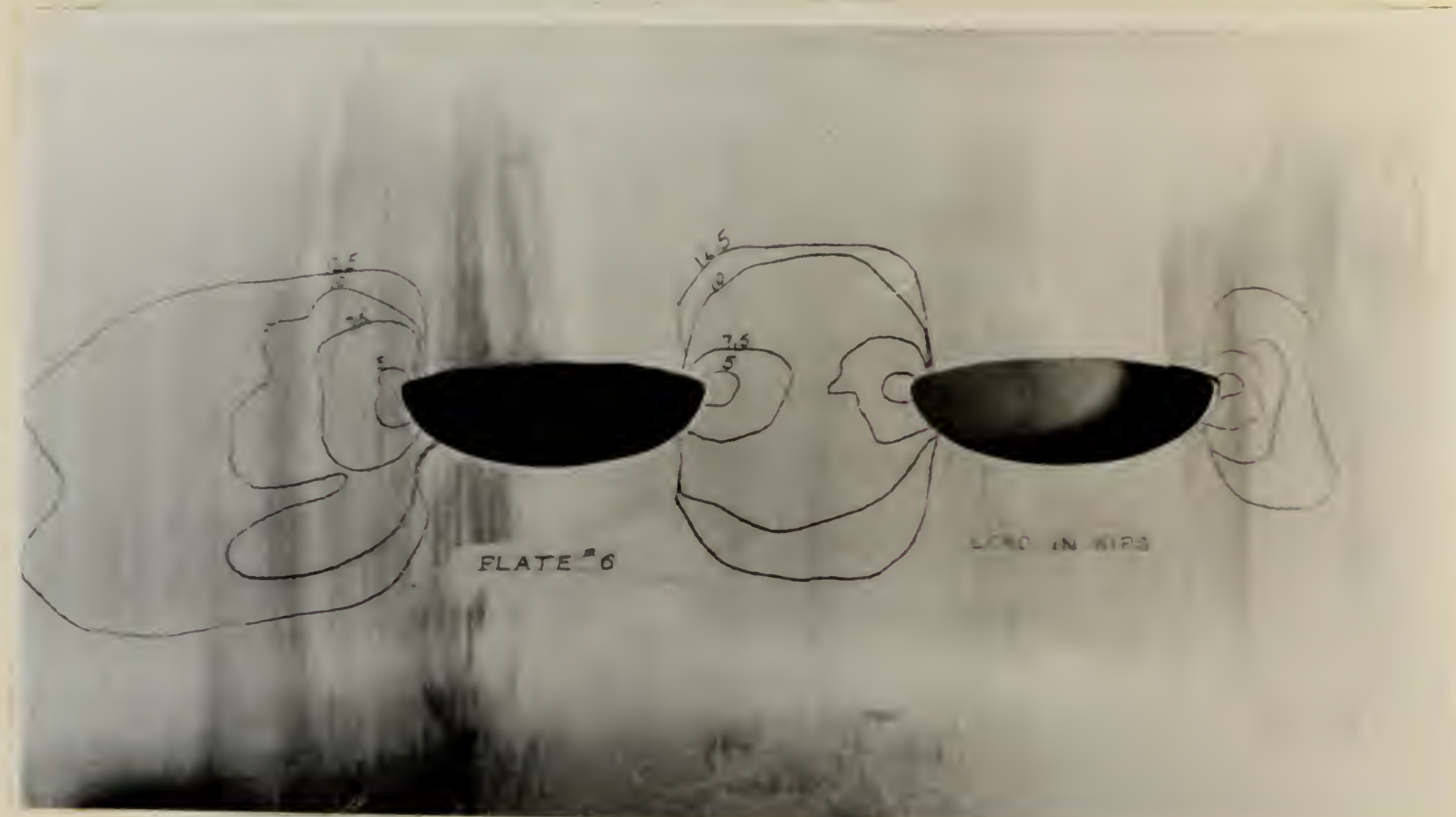


Fig. 11

Wide-view of plate #6 showing isoentatics for loads of 5 kips, 7.5 kips, 10 kips, 12.5 kips.

Fig. 12

Close-up view of plate #6 showing isoentatics for loads of 5 kips to 12.5 kips.

Fig. 13

Plate 7, showing isoentatics for loads 7.5 kips to 25 kips. The isostatics may also be seen.

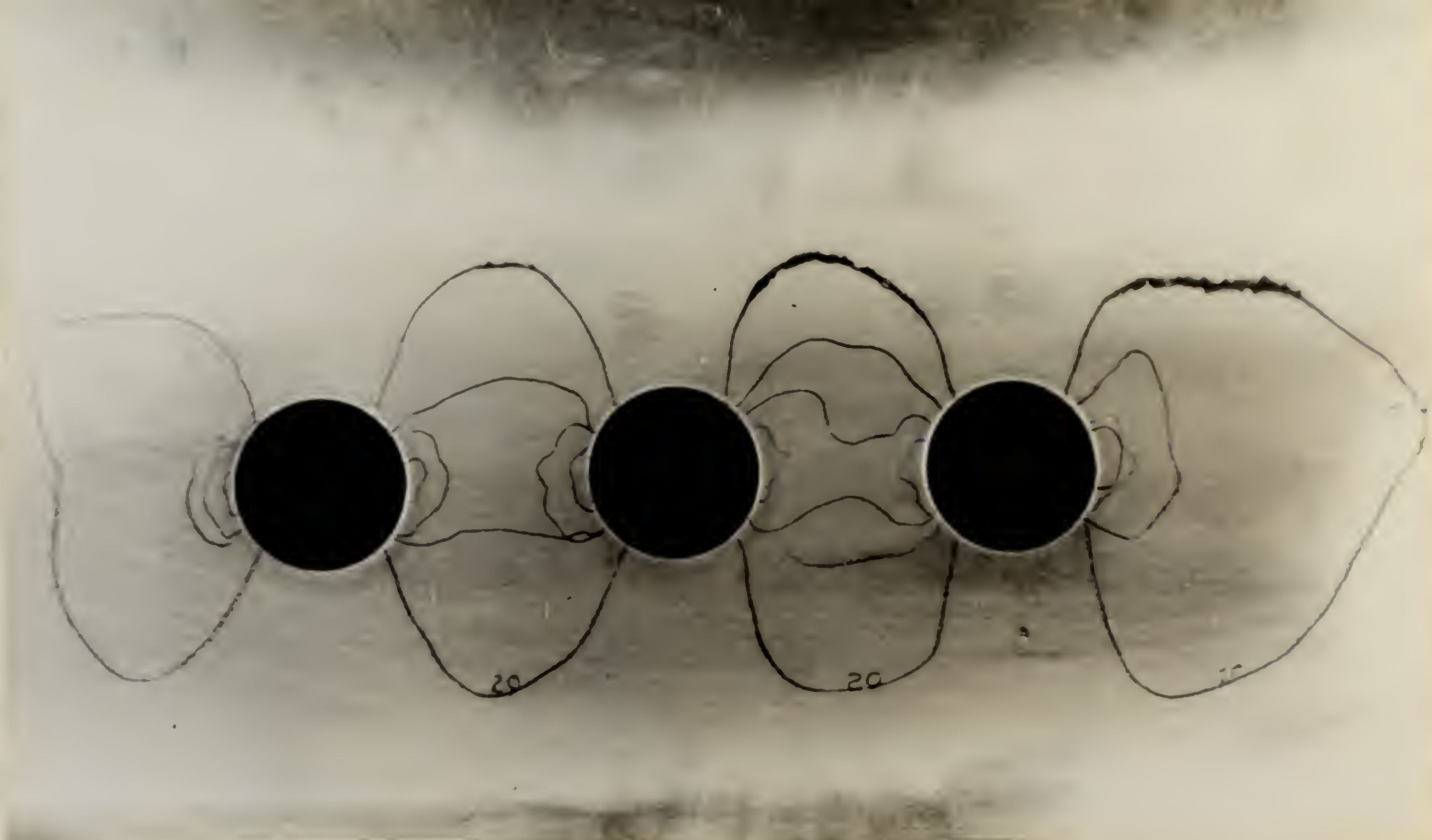


Fig. 14

Close-up view of the three $1\frac{1}{2}$" circular openings of plate #10 after it had been tested. The heavy lines are isoentatics for loads on the plate of 5 kips, 10 kips, 15 kips, and 20 kips. An isoentatic is a line joining the ends of the cracks formed in the lacquer for a particular load. For instance, a load of 5 kips was applied to the plate and the ends of all cracks were connected by a scratch mark which is the smallest ring near the ends of the horizontal diameter of the circles. The load was increased to 10 kips and the ends of the new cracks were joined by a scratch mark which is the next largest ring, and so on up to 20 kips. The plate was etched with red dye to facilitate photographing.

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9. S. Timoshenko, Strength of Materials, Part II, 1943.

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Thesis 7476
M35 Marquardt
An investigation of
stress concentration
factors around selected
openings using the
brittle lacquer technique.